Using Solar-Powered 3-Phase Squirrel Cage Induction Motors as Prime Movers of Synchronous Electric Generators

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Abstract

Most industries and communities in Ghana and around the world depend on synchronous electric generators powered mostly by fuel-run internal combustion engines to augment their energy deficit. Industries, communities and individuals relying on the internal combustion engine driven generators are exposed to pollution, fuel price hikes, frequent fuel shortages, high operational and maintenance costs. In this paper, a solar-powered squirrel cage induction motor was considered as prime mover for the rotating field type synchronous electric generator. The design was simulated using Matlab/Simulink software. Simulation results indicated that the terminal voltage and stator current as a function of time were sinusoidal waveforms of the required magnitude, at constant speed and excitation. The output voltage regulation was achieved not only by the field current excitation but also, the speed regulation of the electric motor. The solar-powered proposed system had capital and installation costs of USD 87,065.00 and 10-year operating cost of USD 43,300.00 giving a total of USD 130,065.00. The total operational cost savings of the new system compared to the existing internal combustion engine powered system for the ten years of operation stood at USD 51,406.16. The new system stands to be recommended to users of synchronous electric generators powered by internal combustion engines in terms of environmental friendliness, minimal maintenance and operating costs.

Keywords: Internal Combustion Engine, Electric Generator, Induction Motor, Solar

1 Introduction

Electrical energy is very crucial to the sustenance of life, from industrial, commercial to domestic use. The most common method of generating electricity is by means of electric generators driven by prime movers. Essentially, they convert mechanical energy into electrical energy. The prime movers could be steam, gas, hydraulic or wind turbines on one hand or diesel, stirling or Internal Combustion (IC) engines on the other hand (Boldea, 2016). Diesel generators are a major source of backup power due to ease of transportation, installation and removal, as well as the mature and stable nature of the diesel industry with reliable suppliers. In the past decade however, diesel prices have more than doubled and high fuel costs have translated into tremendous increases in the cost of energy generation (Pannirselvam *et al.*, 2012). Diesel generators are also a major source of pollution. However, renewable energy sources, such as solar Photovoltaic (PV) and wind power, are clean, affordable, readily available and sustainable (Andrews, 2015; Green, 2012; Mishra and Arya, 2015; Tyagi *et al.*, 2012). They can supplement generators in both grid connected, and off-grid residential and commercial applications (Nayar, 2010).

Over the years, IC engine-powered generators have remained the workhorse of stand-alone electric power generation for domestic consumers, and small- and large-scale industries due to their availability. Good performance indices of diesel electric generators are undermined by the limitations of high running cost of electricity production due to unexpected hikes in fuel prices, air and noise pollution, losses in diesel fuel efficiency and increased operation and maintenance costs due to incomplete combustion of fuel during light loads; and ecological limitations such as carbon monoxide, oxides of sulphur, nitrogen emissions from fuel burning, which have intricate effects on human beings and the climate at large (Boldea, 2016; Boretti, 2019; Reshma, 2019; Zhao *et al.*, 2020). Other typical problems associated with the operation of IC engines include bad fuel mix, failure of ignition, lack of compression, and starter circuit refusing to prime. These pathetic problems would affect a company's production the whole day and in effect cause financial losses. IC engine-powered electric generators offer higher running cost and maintenance charges, excessive environ-mental pollution with undesirable implications due to unacceptable levels of noise and vibration and low thermal and overall efficiency (Boldea, 2016; Boretti, 2019; Reshma, 2019; Zhao *et al.*, 2020). Villalba *et al.* (2019) increased IC engine-powered diesel generator system efficiency by 40.14% by way of cogeneration.

The solar powered Squirrel Cage Induction Motor (SCIM) has been used as a prime mover of a number of machines in reported applications, notable amongst which are rural water pumping (Chinthamalla *et al.*, 2016; Hamdi *et al.*, 2020;

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Poompavai and Kowsalya, 2020; Samal and Das, 2017; Sridhar *et al*., 2015), maize milling machine (Sharma *et al*., 2020) and electric vehicles (Swetha and Surasmi, 2016).

In the works of Salas-Cabrera *et al*. (2010), a shunt-excited DC motor was utilized in a Motor-Generator (M-G) Set. However, focus of their paper was on parameter identification of the M-G Set and not on replacement of an IC engine by the DC electric motor. Yusof and Mat (2018) conducted research on a SCIM that served as replacement of the IC engine in electric vehicle propulsion. This development did not involve the Synchronous Electric Generator (SEG). Electric power production using an M-G Set with its input power desirably from possible renewable energy sources such as solar photovoltaic, wind turbines and fuel cells could curtail on GHG emmisions and improve power efficiency. A possible green energy powering of the SCIM to serve as prime mover of SEG assures of IC engine replacement.

This paper looks at the feasibility of replacing the IC engine with a SCIM. By so doing, our contribution is an extension of the application of solar-powered SCIM as prime mover of the SEG in electric power generation. The rest of this paper is organised as follows: Design concept and criteria, sizing and selection of system elements, system operation and simulation, and cost element computations are presented in Section 2 as the resources and methods used. Section 3 offers the results and discussion and the conclusion is given in Section 4.

2 Resources and Methods Used

The resources and methods employed in this research include collection of performance data on IC engines for analysis, mathematical modelling and computer simulations.

2.1 Design Concept and Criteria

The design work is meant to tap solar energy from the sun with the help of a solar energy tracking system. The output of the solar panel is used to charge a bank of heavy-duty batteries, which output are then inverted to serve as input supply to the 3-phase SCIM, which is mechanically coupled to the rotating field type SEG. With the initial excitation provided by the batteries, the controlled electrical energy output of the generator can feed any desired load. The functional diagram of the system design is given in Fig. 1.

The criteria for system design are as follows: The output of the solar array should match the input requirements of the SCIM, the system should cope with both intermittent and continuous duty cycles, there should be simple means of starting and stopping the M-G Set, the system setup should be user- and environmentally friendly. Methods employed for the replacement of IC engine require system redesign by way of design concept and criteria, selection of 3-phase SCIM, reduction gear, sizing of the solar PV array and batteries, selection of inverter and MPPT-based charge controller, generation of system operation, and simulation of proposed M-G system.

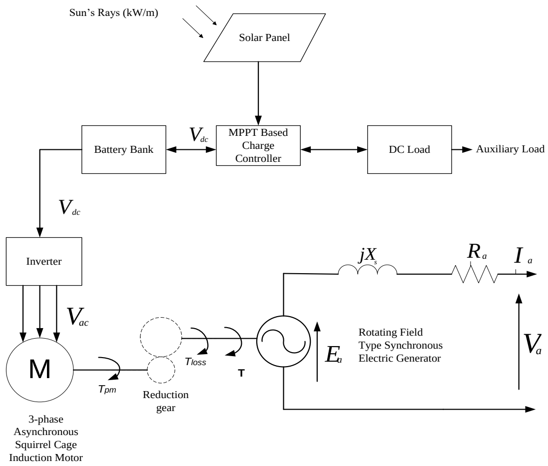

Fig. 1 Functional Diagram of the Solar Powered Motor - Generator System

2.2 Selection of the 3-Phase Squirrel-Cage Induction Motor

The primary technical consideration defining the choice of electric motor for any particular application is the torque required by the load, especially the relationship between the maximum torque generated by the motor (break-down torque) and the torque requirements for start-up (locked rotor torque) and during acceleration periods. Equation (1) gives the input power of the SCIM.

$$P_1 = 3V_1 I_1 \cos\theta_1 \qquad (1)$$

where, P_1 is input power, V_1 is supply voltage, and $\cos\theta_1$ is power factor.

Rotor shaft torque is given as expressed by Equation (2).

$$T_2 = \frac{P_2}{\omega_2} = \frac{60\,P_2}{2\pi\,N_r} = 9.55\frac{P_2}{N_r} \qquad (2)$$

where, T_2 is output torque, P_2 is output power, ω_2 is angular speed, and N_r is rotor speed. Full-load motor efficiency is given by Equation (3).

$$\eta = \frac{P_2}{P_1} \times 100 \qquad (3)$$

The power factor of the SCIM is as given in Equation (4).

$$\cos\theta = \frac{kW}{kVA} \quad (4)$$

As the load on the motor reduces, the magnitude of the active current drawn reduces. From field studies, the diesel generator set at AngloGold Ashanti (AGA), Obuasi Mine uses the Mirless Diesel IC engine with model number (5695-1 WARK KVS-I6), which is required to be replaced) as the prime mover for the SEG and its ratings are as given in Table 1.

Table 1 Field Data on Internal Combustion Engine at AGA

IC Engine Model Number	Rated Speed (rpm)	Rated Output Power (BHP)		Rated Output Power (kW)	
5695-WARK KVS-16	428	Continuous Load	Over Load	Continuous Load	Over Load
		3921	4313	2803	3083

(Source: Anon., 2012)

From Table 1, torque available to the SEG from the IC engine is computed as follows:

$$T_2 = \frac{60P_2}{2\pi N_r} = 9.55\times\frac{60\times2803\times1000}{428}$$
$$= 62.542\ \text{kNm}$$

Theoretically, the selected SCIM must produce approximately 63 kNm to replace the IC engine. Computation of system inertia is aided by Fig. 2 and provided in Equation (5) to Equation (8). On Fig. 2, J_L is inertia of the load $[kg.m^2]$, J_{G1} is inertia of the gear 1 $[kg.m^2]$, J_{G2} is inertia of the gear 2 $[kg.m^2]$, J_M is inertia of the motor $[kg.m^2]$, N_1 is number of gear teeth of the gear 1 [constant], N_2 is number of gear teeth of the gear 2 [constant], m is mass of the load [kg], m_{G1} is mass of the gear 1 [kg], m_{G2} is mass of the gear 2 [kg], D_L is diameter of load [m], ρ is density of the load $[kg.m^3]$, and L is length of the load [m].

$$J_L = \frac{1}{8}m_L D^2 L\left(\frac{N_2^2}{N_1^2}\right) = \frac{\pi}{32}\rho L D^4 L\left(\frac{N_2^2}{N_1^2}\right) \quad (5)$$

$$J_{G1} = \frac{1}{8}m_{G1}D_{G1}^2\left(\frac{N_2^2}{N_1^2}\right) \quad (6)$$

$$J_{G2} = \frac{1}{8}m_{G2}D_{G2}^2 \quad (7)$$

$$J_T = J_L + J_{G1} + J_{G2} + J_M \quad (8)$$

where, J_T is total inertia of the system $[kg.m^2]$.

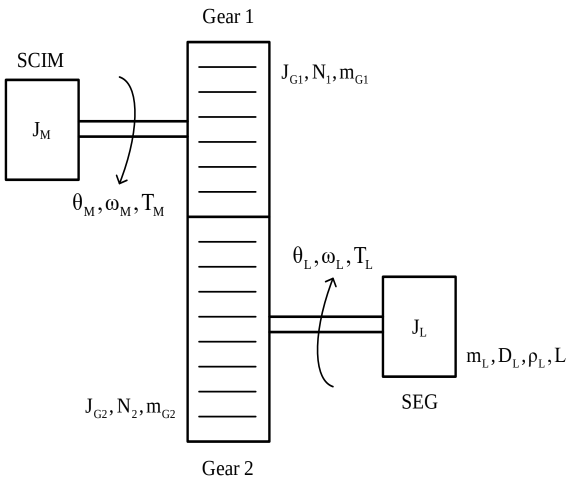

Fig. 2 Rotational Transmission of SCIM, Gears and SEG as Load

Torque equation is given by Equation (9).

$$T_\alpha = J_T a = (J_L + J_{G1} + J_{G2} + J_M)\frac{\omega_M - \omega_0}{t} \quad (9)$$

where, T_a is motor acceleration torque in Nm, ω_0 is initial velocity of the motor, ω_M is final velocity of the motor, and t is time for velocity change.

The total computed torque and the required motor torque are presented using Equation (10) and Equation (11), respectively.

$$T_T = T_\alpha + T_L \quad (10)$$

$$T_m = k_s T_T \quad (11)$$

where, T_T is total calculated torque, T_L is load torque, T_m is required motor torque. Field data collected on the SEG is presented in Table 2.

Table 2 Field Data on the Rotating Field Type Synchronous Electric Generator

Parameter	Value
Rated Output (kVA)	5,687.5
Output Voltage (kV)	6.6
Rated Speed (rpm)	428
Rated Current (A)	322.5
Excitation Current (A)	20
Efficiency (%)	96.9
Power Factor (Cos f)	0.8

(Source: Anon., 2012)

For $J_L = 415\ kg.m^2$, $J_{G1} = 10\ kg.m^2$, $J_{G2} = 10\ kg.m^2$, $J_M = 53\ kg.m^2$ and $T_L = 300$ Nm. Total moment of inertia is given by Equation (12).

$$J_T = J_L + J_{G1} + J_{G2} + J_M \quad (12)$$
$$= (415 + 10 + 10 + 53)\ \text{kg.m}^2$$
$$= 488\ \text{kg.m}^2$$

From Equation (9),

$$a = \frac{428 - 0}{60} = 7.133\ \text{rad}/\text{sec}$$

Therefore,

$$T_\alpha = J_T\alpha = 488 \times 7.133 = 3480.94\ \text{kgm}^2/\text{s}^2$$

For T_L = 300 Nm, and from Equation (10),

$$T_T = 3480.904 + 300 = 3780.904\ \text{Nm}$$

Required motor torque using $k_s = 2$ gives:

$$T_m = k_S T_T [\text{Nm}] = 2 \times 3780.904\ \text{Nm}$$
$$= 7561.808\ \text{Nm} = 7.5618\ \text{kNm}$$

From the manufacturer's data sheet, the motor type C4M450LB4 is selected based on its output torque and its specifications are presented in Table 3. Parameters of the reduction gear are given in Table 4. The reduction gear is selected based on the duty cycle, speed classification and torque requirement.

2.3 Sizing of the Solar Panel and Batteries

Due consideration is given to calculating the size of PV panel, the sizing of the batteries and subsequently the inverters for the application. Factors considered in calculating the size of the PV array are: The solar PV output must match the input requirements of the system with a tolerance of ± 5 to ± 10%, daily peak sun hours, efficiency and temperature losses of the batteries, Ampere-hour requirement per day or week, shading coefficient and derating factor, and operation duration per day or week. Sizing of the batteries was done based on total power requirement of the SCIM plus 5% tolerance to compensate for temperature losses, derating factor of the solar PV array and the shading coefficient. The maximum daily consumption of a system is given by Equation (13).

$$\text{DyC} = \text{kW} \times \text{Hours Worked} \quad (13)$$

where, DyC is daily consumption, and kW is kilowatt rating.

$$\text{DyC} = 125 \times 1000 + \left(\frac{5}{100} \times 125000\right) \times 5\ \text{hrs}$$
$$= 656.25\ \text{kWh}$$

Table 3 Manufacturer's Data of Selected Squirrel-Cage Induction Motor

Parameter	Value
Motor SCIM Type	C4M450 LB4
Rated Power (kW@50Hz	125
Supply Voltage (V)	400
Rated Speed (rpm)	1492
Torque (Nm)	7993
Current (A)	117
Efficiency (%)	96.9
Power Factor	0.92
Moment of Inertia (kgm^2)	33

Table 4 Parameters of the Reduction Gear

Parameter	Requirement
Type of Drive Machine	3-phase Squirrel Cage Induction Motor
Speed of Drive Machine (rpm)	1492
Speed of Driven Load (rpm)	428
Duty Cycle of the System	Intermittent duty
Moment of Inertia of Gear System	(10-20) kgm^2
Total Moment of Inertia of Drive Train	(488-500) kgm^2
Output Torque of Drive Machine	7.6 kNm
Service Factor of the System	2.0
Speed Classification	Constant Speed

The ratio of total watt-hour per day to the minimum charging hour per day gives the total power required by the system per day and this is expressed by Equation (14).

$$P_{day} = \frac{(PC_{max})_{day}}{(CH)_{day}} \quad (14)$$

where, P_{day} is total power required per day, $(PC_{max})_{day}$ is maximum daily consumption, $(CH)_{day}$ is charging hours per day.

$$P_{day} = \frac{656.25\ \text{kWh}}{8\ \text{hrs}} = 82.031\ \text{kW}$$

For a panel capacity of 500 W, the total number of solar panels required is given by Equation (15).

$$P_T = \frac{P_{day}}{P_{PVmax}} \quad (15)$$

where, P_T is total number of panels, P_{PVmax} is maximum power of the PV panel.

$$P_T = \frac{82031\text{W}}{500\text{W}} = 164.06 \approx 165$$

The solar PV is sized giving consideration to daily peak sun hours, battery efficiency, temperature loss, derating factor of the PV array and the shading coefficient of the installation. If DC source requirement is 48 V and battery capacity of 24 V, 200 AH then the number of batteries required is given by Equation (16).

$$NB_{strings} = \frac{(PC_{max})_{day}}{V_{IN}} \qquad (16)$$

where, $NB_{strings}$ is number of battery strings, and V_{IN} is input voltage of the inverter.

$$NB_{strings} = \frac{656250 \text{ Wh}}{48 \text{ V}} = 13671.87 \text{ AH}$$

Number of batteries in series is given by Equation (17)

$$NB_{series} = \frac{NB_{strings}}{AH_{battery}} \qquad (17)$$

where, NB_{series} is number of batteries in series, and $AH_{battery}$ is ampere-hour rating of battery.

$$NB_{series} = \frac{13677.87 \text{ AH}}{200 \text{ AH}} = 68.35 \text{ » } 69$$

From the above calculations 165 pieces of 500 W solar PV panels and 69 pieces of 12 V 200 AH heavy duty batteries arranged in series 4 rows by 18 strings are required. The inverter size required to supply the calculated power must be slightly above the maximum power required by the system per day. Therefore, 3 pieces of 48 V, 30 kW inverter with collective surge watt rating slightly higher than the maximum power is chosen.

2.4 Selection of MPPT–based Charge Controller

The solar charge controller is typically rated against amperage and voltage capacities. Sizing and selection of solar charge controller to match the voltage of PV array and batteries are very crucial for better controllability and high performance. Sizing of controller depends on the total PV input current which is delivered to the controller and also on the PV panel configuration (series or parallel configuration).

According to standard practice, the sizing of solar charge controller is to take the short circuit current (I_{sc}) of the PV array, and multiply it by 1.3 as factor of safety.

Solar charge controller rating = Total short circuit current of PV array multiplied by 1.3.
Short circuit current per string I_{sc} = 9.12 A

Therefore, solar charge controller rating = (4 strings × 9.12 A) × 1.3 = 47.42 A. Hence, the solar charge controller selected should be rated at least 50 A at 48 V or greater.

2.5 System Operation

Operation of the setup is presented in Fig. 3.

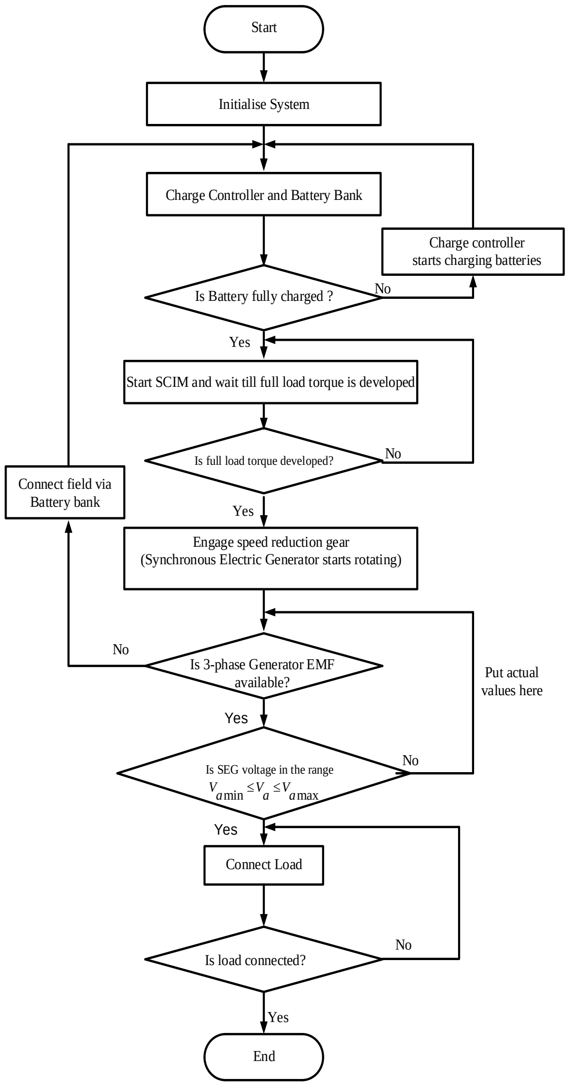

Fig. 3 Flowchart of the Solar Powered Motor-Generator System

Step 1: *System initialisation*
System starts, initialisation process begins, the system checks the status of the battery bank and the charge controller. If all conditions are normal start the SCIM otherwise, command charge controller to start charging the batteries.

Step 2: Component engagement
Engage the speed reduction gear and wait until full load torque is developed, otherwise, wait or revert to Step 1.

Step 3: Emf availability
SEG starts rotating, check the output of the SEG for EMF otherwise check supply of the field else connect the SEG field via the battery bank.

Step 4: Values conditioning
Measure the value of V_G and ascertain whether the values are within the range of $V_{Gmin} \leq V_G \leq V_{Gmax}$ otherwise adjust the field excitation of the SEG.

Step 5: Ending criteria
If measured V_G values are within the acceptable range, connect the load.

Step 6: if the load is connected, then end process else check whether V_G value is satisfactory in order to connect the load.

2.6 Simulation of Proposed Motor-Generator System

The proposed system is simulated using Matlab Simulink software version 2014b. The modelled system is depicted in Fig. 4. A programmable voltage source represents the solar inverted source, connected electrically to the 3-phase induction motor which is mechanically coupled to the synchronous machine as a generator. The setup is connected to a load via an instrumentation panel to give information on the performance of the system.

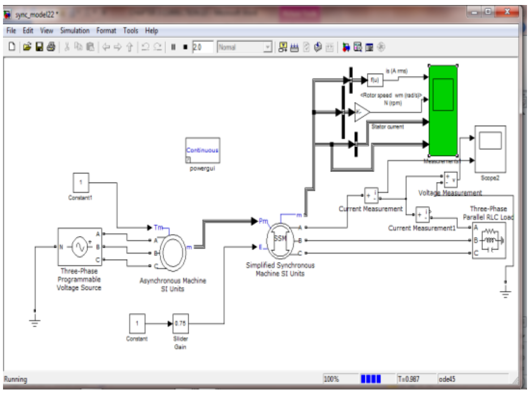

Fig. 4 Modelling of the Proposed System in Matlab Simulink Software

2.7 Computation of Cost Elements

According to Maier (2014), operating cost of solar-powered system comprises installation, replacement and maintenance costs, cleaning and monitoring costs. In this research, installation cost is considered as part of capital cost and not part of operations. More so, the installation cost is borne once and it is not recurring. The batteries and the inverters are replaced every five years. For the IC engine powered system, operating cost comprises fuel, lubrication, yearly maintenance and servicing, and Environmental Protection Agency (EPA) fixed charges. Ideally, the fuel cost of diesel generator is a function of capacity of the connected load, the type of diesel generator, rating of the diesel generator, the quality of the fuel, ambient temperature, and humidity (Adefarati and Bansal, 2019). According to them, the fuel cost of the diesel generator can be expressed as in Equation (18).

$$FC_i = a_i P_{gen}(i,t) + b_i P_{gen}(i,t) + C_i \text{ (USD/h)} \quad (18)$$

where, a_i, b_i, and c_i are cost coefficients of the diesel generator, FC_i is the fuel cost of diesel generator, and P_{gen} is the power generated by the diesel generator. The fuel cost could be equally computed based on the number of litres consumed per year and the average annual increment in fuel cost per litre. The lubrication cost is conducted quarterly to achieve the litres used per year The operating cost is found using Equation (19).

$$OC_{SPi} = CM_i + IR_i + BR_i \quad (19)$$

where, OC_{SPi} is the ith year operating cost of solar powered system, CM_i is the ith year cost of maintenance, IR_i is the cost of solar power inverter replacement in the 5th and 10th years only, BR_i is the cost of battery replacement in the 5th and 10th years only. For the first year, CM_i = USD 2,000.00, in the fifth and 10th years IR_5 = USD 1,350.00 and IR_{10} = USD 1,350.00, respectively whilst BR_5 = USD 12,300.00 and BR_{10} = USD 12,300.00, respectively. The operating cost of the IC engine system is given by Equation (20).

$$OC_{ICi} = FC_i + LC_i + MC_i + EPA_{Fi} \quad (20)$$

where, OC_{ICi} is the ith year operating cost of IC engine powered system, FC_i is the ith year fuel cost, LC_i is the ith year cost of lubrication, MC_i is maintenance cost for the ith year and EPA_{Fi} is the Environmental Protection Agency fixed charges for every year. For the first year, FC_i = USD 27,600.00, LC_i = USD 1,575.00, MC_i = USD 2,000.00 and EPA_{Fi} = 1,000.00.

Operating costs of subsequent years are computed taking cognizance of yearly increment in maintenance cost of 5% for both systems, then 6.5% and 8% annual increment on fuel and lubricants, respectively. Even though the cost of solar power inverters and the batteries are reported to be reducing each year, in this research they are considered fixed. The percentage annual cost savings are computed using Equation (21) and the total cost savings for the ten years are given by Equation (22).

$$CS_i = \frac{OC_{SPi} - OC_{ICi}}{OC_{ICi}} \times 100 \qquad (21)$$

$$T_{CS} = \sum_{i=1}^{10} CS_i \qquad (22)$$

where, CS_i is the ith year cost saving and T_{CS} is the total cost savings for the 10 years. The outcome of cost savings are reported in Section 3.2.

3 Results and Discussion

3.1 Simulation Results

The simulation results are shown in Fig. 5, Fig. 6 and Fig. 7. From Fig. 5, output voltage waveform of the system as a function of time is a sinusoidal wave with the required amplitude, which corresponds to the output voltage of the SEG. Fig. 6 depicts the waveform of the stator current as a function of time, at a constant excitation with a phase difference of 120^o as expected. The stator currents are in phase with the rotor speed and the magnitude of the excitation voltage. Fig. 7 shows the speed of the rotor as a function of time. The rotor speed is in phase with the output emf generated. It means when the rotor rotates for one revolution, the induced sinusoidal emf varies for one cycle such that if the rotor position is measured in mechanical degrees or radians, it will be equal to measuring the phase angle of the flux or the induced emf in electrical degrees or radians.

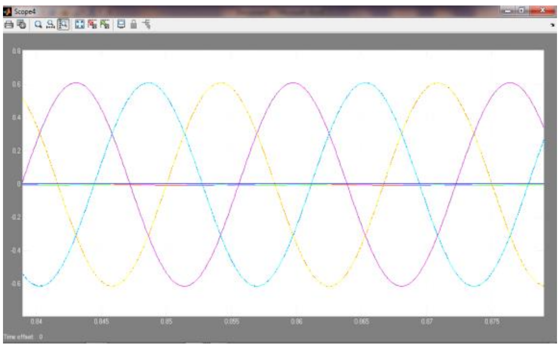

Fig. 5 A Graph of Output Voltage versus Time

Fig. 6 A Graph of Stator Current versus Time

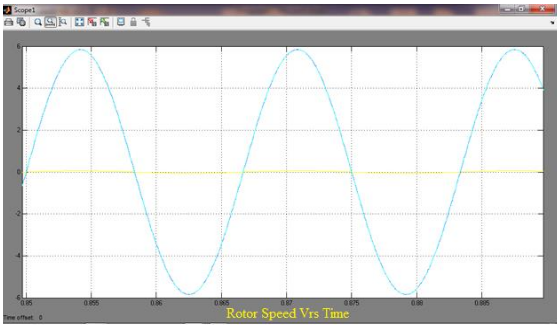

Fig. 7 A Graph of Rotor Speed versus Time

3.2 Cost Analysis

The discussion on cost implications centres on system comparison in terms of capital and installation, and operational costs. Table 5 and Table 6 show the capital and installation costs whiles Table 7 depicts a comparison of the operating cost of the solar-powered 3-phase SCIM and the IC engine driven SEG for the 10-year period. From Table 7, it can be seen that an appreciable decrease in cost of electric power production when the IC engine is replaced with the solar powered 3-phase SCIM is achievable. From Table 6 and Table 7, it can be seen that the total cost of procuring, installing and operating for ten years the new system amounted to USD 130, 365.00.

Table 5 Capital and Installation Costs of the IC Engine System

Material	Qty	Unit Price (USD)	Total (USD)
3921 BHP IC Engine	1	10,000.00	10,000.00
Transportation Cost			2,000.00
Installation Cost	1	5,000.00	5,000.00
Sub - Total			**17,000.00**
Miscellaneous			1.700.00
Grand Total			**18,700.00**

Table 6 Capital and Installation Costs of the Solar Powered System

Material	Qty	Unit Price (USD)	Total (USD)
1250 kW 3-Phase SCIM	1	2,000.00	2,000.00
Reduction Gear	1	3,000.00	3,000.00
1000 W PV Modules	197	250.00	49,250.00
24 V Lead Acid Battery	82	150.00	12,300.00
3-Phase Sine Wave Inverter and Charge Controller	3	450.00	1,350.00
Transportation Cost			3,000.00
Installation Cost	1	5,000.00	8,500.00
Sub-Total			**79,150.00**
Miscellaneous			7,915.00
Grand Total			**87,065.00**

Table 7 Operating Cost and Associated Cost Savings of the Solar Powered and IC Engine Systems for 10 Years

Year	IC Engine System (USD)	Solar Powered System (USD)	Cumulative Cost Savings (USD)
1.	32,275.00	2,000.00	30,275.00
2.	35,300.00	2,000.00	33,300.00
3.	38,456.94	2,000.00	36,456.94
4.	41,754.49	2,000.00	39,754.47
5.	45,201.80	13,650.00	31,551.80
6.	48,808.77	2,000.00	46,808.77
7.	52,585.85	2,000.00	50,585.85
8.	56,544.21	2,000.00	54,544.21
9.	60,695.75	2,000.00	58,695.75
10.	65,053.16	13,650.00	51,403.16

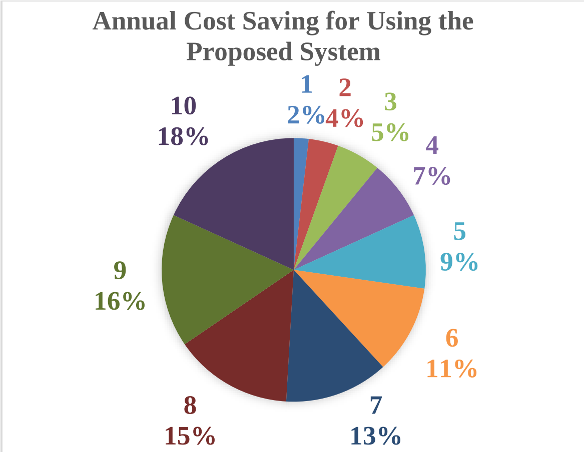

Fig. 8 Percentage Annual Cost Savings for a 10-Year Period

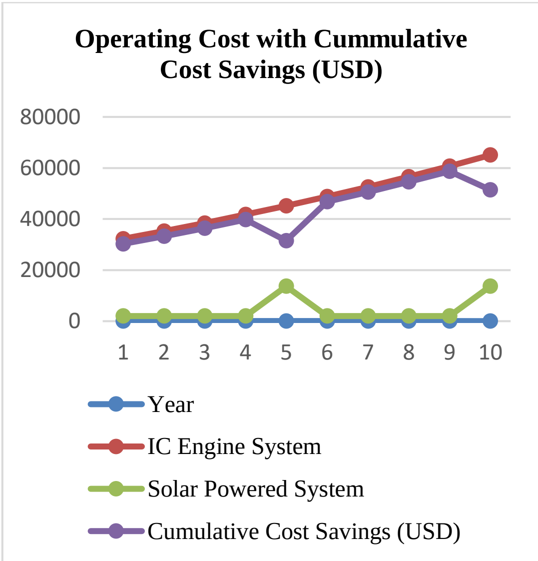

Fig. 9 Graphs of Operating Costs with Cumulative Cost Savings for a 10–Year Period

The Fig. 8 indicates the percentage annual cost savings whilst Fig. 9 shows the line graphs of the cumulative cost savings of both systems for the period of 10 years when the solar powered 3-phase SCIM is used as the prime mover of the SEG. In Fig. 8, each progressing year recorded higher annual cost savings. Typically, 9% was achieved in the fifth year and the highest value of 18% corresponded to the tenth year. The drops in cumulative cost savings in the fifth and tenth years in Fig. 9 were due to replacement of the solar power inverter and the batteries.

4 Conclusion

Generating electrical energy using solar-powered 3-phase SCIM as prime movers for rotating type SEG has been developed. There are comparatively minimal operating charges in using the proposed system. The proposed setup can be introduced as a simple micro-grid, backup, or standalone and it could prove its usefulness in domestic, commercial and industrial applications. The system assures of robustness as the terminal voltage of SEG can be controlled easily by regulating the speed of the 3-phase SCIM. The proposed system is environmentally friendly, cost effective, requires little maintenance and gives relatively minimal operating charges.

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